Crop Productivity and Nutrient Dynamics in a Shrub-Based Farming System of the Sahel

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ABSTRACT

Piliostigma reticulatum (DC.) Hochst., an indigenous shrub, forms an important vegetative component of parkland cropping systems in the Sahel; however, its biophysical interactions with soil and crops are not well understood. Therefore, the objectives were to determine the impact of *P. reticulatum*, under varying fertilizer rates, on crop yield response and soil nutrient dynamics. The experiment had a split-plot factorial design, where the main plot was shrub (presence or absence) and the subplot was fertilizer rate (0, 0.5, 1.0, or 1.5 times the recommended N–P–K fertilizer rate) applied to a peanut (*Arachis hypogaea* L.)–pearl millet [*Pennisetum glaucum* (L.) R. Br.] rotation. In 3 of the 4 yr, *P. reticulatum* improved or had no effect on crop yields when averaged across fertilizer rates. Overall, millet and peanut biomass and N and P uptake by millet increased in the presence of shrubs and with increasing fertilizer rate. Contrary to P, inorganic N in the soils changed very rapidly, reaching very low levels by the end of the growing season. The N content of soil leachates below the rooting zone was generally lower beneath than outside the shrub canopy, suggesting that the shrub conserves N that is otherwise lost through leaching. *Piliostigma reticulatum* increased particulate organic matter, indicating that this shrub improved soil quality. These results suggest that *P. reticulatum*, under nonthermal management and a higher density than typically found in farmers' fields, has ecological benefits with improved soils and reduced loss of N, which has implications throughout the Sahel.

Soil organic matter is depleted in the soils of sub-Saharan Africa due to anthropogenic activities such as deforestation and the burning of biomass. This results in an inadequate replenishment of soil nutrients, contributing to unsustainable and low-production agriculture (Tilander et al., 1995; Lal, 2002; Mafongoya et al., 2006a). The recovery of inorganic nutrients from fertilizers by crops is generally very low in the Sahel. For N, recovery rates of <30% have been reported, caused by intense leaching of NO_3–N below the rooting zones of crops (Nyamangara et al., 2003; Mafongoya et al., 2006a). Although the mobility of P in soils is relatively low, the soils of sub-Saharan Africa generally have high levels of P sorption that significantly reduces availability to plants of inorganic P fertilizer added to soils (Dossa et al., 2008).

Another important aspect for optimal functioning of soils that would deliver services for agriculture and reduce soil erosion is soil structure, a property largely defined by aggregation (Six et al., 2004). It follows that well-aggregated soil is critical for nutrient and water use efficiency, particularly in semiarid regions such as the Sahel. Aggregates provide porosity, which improves water retention, enables better root growth, and improves the recovery of nutrients and water for crops. Inputs of organic matter and the presence of roots are important in developing and maintaining soil structure through aggregation (Six et al., 2004).

It is now well established that organic inputs are essential for developing the quality of soils for sustainable and productive cropping systems in the Sahel. A judicious combination of organic and inorganic amendments optimizes nutrient and water efficiencies (Bationo et al., 1993; Sanchez et al., 1997; Badiane et al., 2000; Akinnifesi et al., 2007; Tittonell et al., 2008; Dossa et al., 2012). Additionally, woody species in cropped fields (agroforestry), besides providing organic inputs, have root systems that can improve chemical and physical properties of the soil (Dancette and Poulain, 1968; Kang et al., 1984; Young, 1989; Depommier et al., 1992; Kater et al., 1992; Rhoades, 1996; Buresh and Tian, 1997; Mafongoya et al., 2006b).

Agroforestry systems in semiarid regions can capture N through biological N_2 fixation by leguminous woody species (Mafongoya et al., 2006b) and recover nutrients from subsoil layers not explored by the crop (Hartemink et al., 2000;

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Abbreviations: POM, particulate organic matter.

Mafongoya et al., 2006b). Such systems can also reduce nutrient loss (Gathumbi et al., 2004).

A major challenge for the adoption of agroforestry systems is that the woody component not be competitive with crops. Indeed, parkland agroforestry with tree species has had only limited success (Rhoades, 1996; Buresh and Tian, 1997; Mercer, 2004). In contrast, recent research on *Guiera senegalensis* J.F. Gmel., a native shrub that Sahelian farmers allow in cropped fields, has shown great potential for improving cropping systems. This species in Senegal has been shown to improve soil quality (Dossa et al., 2010), be a major source of C inputs (Lufafa et al., 2008), not be competitive for water (Kizito et al., 2007), and most importantly, dramatically increased productivity of two important semiarid crops—peanut and millet (Dossa et al., 2012).

In Senegal and throughout the Sahel there is another shrub species, similar to *G. senegalensis*, which also coexists with crops. This is *P. reticulatum* (as far as we know a non-nodulating legume), which is found to varying degrees growing in cropped fields in regions that are south of and wetter than areas where *G. senegalensis* is typically found in the Sahel (Lufafa et al., 2008). Unlike trees, which are vulnerable to overexploitation (Tilander et al., 1995; Wezel, 2000) and are slow growing, this shrub is adapted to yearly pruning and can establish relatively quickly, similar to *G. senegalensis* (Seghieri et al., 2005).

Traditional management of *P. reticulatum* includes annual spring coppicing, accompanied by burning of aboveground residue, before cultivation of row crops. *Pilisotigma reticulatum* has >90% of its root biomass in the 0.2- to 0.5-m depth range and preferentially utilizes water below 1.1 m (Kizito et al., 2006) so that it does not compete with adjacent crops for water (Kizito et al., 2007). In addition, *P. reticulatum* creates islands of fertility, with higher C and N beneath than outside the canopy (Dossa et al., 2008; 2010). This horizontal heterogeneity in nutrient distribution associated with shrubs may influence plant-nutrient dynamics and ultimately crop productivity.

Studies have shown the potential of *P. reticulatum* residues as mulch (Diack et al., 2000; Iyamuremye et al., 2000) that can be decomposed by soil microorganisms and release nutrients (Iyamuremye et al., 2000; Dossa et al., 2009); along with *G. senegalensis*, *P. reticulatum* provides significantly greater C inputs than crop or animal organic inputs in Senegal (Lufafa et al., 2008). These studies, however, give only indirect evidence for improving soils for crop production (Diack et al., 2000; Iyamuremye et al., 2000), and there are no studies on crop yields at the field scale. Therefore, the objectives of this study were to investigate the impact of the presence of *P. reticulatum* and fertilizer rate in a peanut–pearl millet rotation on crop yield, N and P uptake by shrubs and crops, as well as soil nutrient dynamics.

MATERIALS AND METHODS
Study Site

The experimental site is in Senegal, West Africa, near Nioro in the southern region of the Peanut Basin (13°45′ N, 15°47′ W, 18 m asl). The two major crops cultivated at the site are millet and peanut.

The mean annual precipitation is 750 mm and mainly comes between July and September. The mean air temperature ranges from 20.0 to 35.7°C. Cumulative annual rainfall at the site was
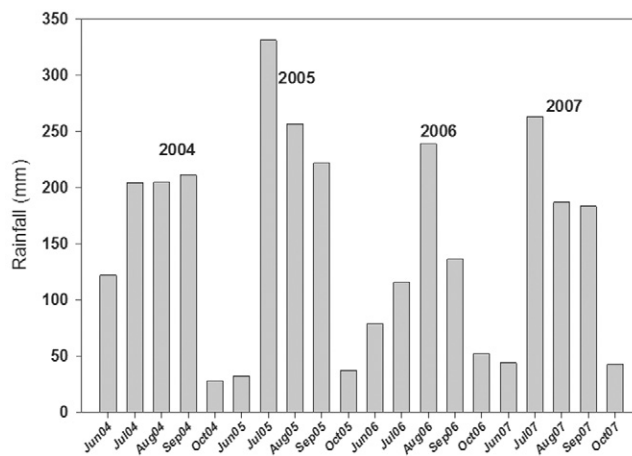

Fig. 1. Rainfall distribution at Nioro, Senegal, from 2004 to 2007.

740, 900, 622, and 720 mm in 2004, 2005, 2006, and 2007, respectively. The rainfall pattern during the study period is shown in Fig. 1.

The soil is a Deck–Dior (Badiane et al., 2000) loamy sand (a fine-sandy, mixed Haplic Ferric Lixisol [IUSS Working Group WRB, 2006]), a leached ferrugineous tropical soil. The topsoil (0–10 cm) has a sand content of >90%, organic matter and total N contents of 0.52 and 0.03%, respectively, total P content of 70 mg kg^{-1}, and a mean pH (in water) of 6.2. The dominant shrub species is *P. reticulatum*. The typical shrub is 1 m high by 1 to 2 m in diameter and has multiple shoots. Left uncut it can grow into a tree, but in farmers' fields it maintains a shrub-like growth pattern because of annual coppicing. Herbaceous annual vegetation in the intershrub space is dominated by *Cenchrus biflorus* Roxb., *Digitaria lecardii* (Pilg.) Stapf., *Eragrostis tremula* (Hochst. ex Steud.), *Indigofera pulchra* Willd., *Mitracarpus villosus* (L.) DC, and *Stylosanthes fruticosa* (Retz.) Alston (Dossa et al., 2010).

Experimental Design

A 0.5-ha field with preexisting shrubs was selected that had been under local farmer management for at least the last 50 yr. The site had been cropped continuously in a peanut–millet rotation before the experiment but left fallow for 3 yr before the start of the experiment. The experimental design was a randomized block split-plot, with the presence or absence of the shrub as the main plot and fertilizer rate as the subplot with four replicates.

The main plots, with and without shrubs, were established in the winter of 2003. The no-shrub plots had the existing shrubs removed manually; most shrub plots had four to seven shrubs per plot (except for six subplots that had lower stand levels and had seedlings transplanted to achieve a similar density as the other shrub plots in 2003) for a stand density of 888 to 1555 shrubs ha^{-1}. This stand density for *P. reticulatum* is substantially higher than the average density of 185 shrubs ha^{-1} in the surrounding fields (Kizito et al., 2006) and that reported by Lufafa et al. (2008) for the Peanut Basin of 134 to 288 plants ha^{-1}. Shrubs were randomly but relatively evenly distributed. The following summer, millet was planted on all plots and fertilized with 68.5 kg N, 15 kg P, and 15 kg K ha^{-1} to allow the plots to equilibrate for 1 yr before initiation of the experiment.

Main plot sizes were 46 by 4.5 m and subplot sizes were 10 by 4.5 m. There was a 2-m gap between adjacent plots and 3-m gap between blocks. All plots had a crop rotation of 55-437 peanut and Souna 3 millet during the experimental period from 2004 to 2007. This is the dominant farmer practice in the region.

The subplot fertilizer treatments were 0, 0.5, 1.0, or 1.5 times the recommended fertilizer rate for each crop. For peanut, the recommended rate was 9 kg N, 30 kg P, and 15 kg K ha^{-1}. The inorganic fertilizer was manually broadcast after peanut germination followed by incorporation by hand hoeing to a depth of 5 to 8 cm. The recommended fertilizer rate for millet was 22.5 kg N, 15 kg P, and 15 kg K ha^{-1}. This inorganic fertilizer was applied at planting followed by 46 kg N ha^{-1} as urea (a split of 23 kg each at 2 and 4 wk after planting). The fertilizer applied at planting was incorporated, whereas the subsequent N applications were broadcast.

In late June of 2004, peanut was planted 15 cm apart, with a distance of 50 cm between rows. Because of irregular germination, the few plants that emerged were removed and the plots were resown after fertilizer had been applied. During the second growing season in 2005, millet was planted in June at a 1- by 1-m distance, with four to six seeds per hole. After germination, the plants were thinned to one to two plants per hole. Weeding was done by a shallow cultivator drawn by animal traction to a 5-cm depth. In the fallow period, there was no weeding and shrubs were allowed to regrow. During the cropping season until the crops were near maturity, shrubs were coppiced in April, cut into 5- to 10-cm lengths, and returned to the soil (this followed standard farmer practices in terms of coppicing except that the residue was not burned). The aboveground crop biomass, however, was managed according to farmers' practices, where aboveground millet was left in the plots but peanut residue was removed (peanut residue is typically removed for livestock fodder). This peanut–millet sequence was repeated with peanut in 2006 and millet in 2007 following the management practices described above.

Soil, Sampling, and Soil Solution Collection

Soil samples for chemical analyses were taken from each subplot before fertilizer treatments and monthly after fertilizer application. For each sampling date, 10 soil cores (2.5-cm diameter) per subplot were randomly taken to a 10-cm depth along the diagonals within the inner two-thirds of each subplot. The cores were homogenized, air dried, and sieved to pass a 2-mm sieve; a 200-g sample was kept in a sealed plastic bag at room temperature for chemical analyses.

Lysimeters were used for soil water sampling and were installed at the 55- to 60-cm depth in the subplots receiving zero and the highest rate of fertilizer (0 and 1.5 times the recommended fertilizer rate, respectively) in the presence or absence of shrubs. The lysimeters consisted of a polyvinyl chloride tube (~2.5-cm diam.) fitted with a porous ceramic cup at one end; the other end was sealed with a rubber stopper. Before installation, the ceramic cups were washed with deionized water and the first collected sample was discarded to allow the cups to equilibrate with the soil.

In each subplot with shrubs, one lysimeter was placed in the middle of the canopy zone and one in the outer edge of the canopy of two representative shrubs (based on canopy height and diameter). In the subplots without shrubs, the porous cups were randomly placed, one between two plants in a row and the other one between two rows at the midpoint formed by four plants. After installing the lysimeter before planting of the crop in 2004, a slurry of clay (approximately 2:1 water/clay mixture) was used to seal the base of the tube at the soil surface to avoid possible artifacts caused by water infiltration along the tubes during rainfall events. The lysimeters, as described above, were placed in two of the four blocks of the major experimental design. From June to August in 2004 and from June to October in 2005, soil solution was sampled every 2 wk. Before each sampling, a suction of 72 kPa was applied to the lysimeters using a hand-held vacuum pump, and soil water samples were collected using a 50-mL syringe. The collected soil solution samples were composited per replicate and transported to the laboratory, where two to three drops of chloroform were add and the samples were frozen until analysis.

Crop Yield Assessment and Plant Sampling

At crop maturity, the inner two-thirds of each subplot was harvested. In the case of peanut, the entire plants were mechanically removed from the plots, sun dried for 4 to 5 d, and pods were removed from the biomass. Millet grain yield was determined by harvesting millet ears from the entire harvested area. The ears were sun dried, which resulted in a water content of <10%, and shelled to yield dry millet grain per subplot. The aboveground biomass of millet (leaf + stalk) was cut at the soil surface and the fresh weight was recorded. Composite samples of approximately 500 g were taken for water content determination after drying at 65°C to a constant weight.

The coppiced shrub aboveground biomass at the beginning of each cropping season and during the crop growing season was sorted into leaf and stem components and the fresh weight was determined for each component. For each biomass component, a composite sample of approximately 500 g was taken for water content determination after drying at 65°C to a constant weight. Representative samples of the different plant tissues were ground with a Wiley mill through a 2-mm mesh and kept in sealed plastic bags for subsequent chemical analyses. The remainder of the leaf and stem residue (chopped into ~5–10-cm lengths) was returned to the soil (it was lightly incorporated just before planting in the spring and placed on the soil surface during the growing season).

Laboratory Procedures

Particulate organic matter (POM) determination (undecomposed plant and microbial debris), on 0- to 10-cm-depth soils sampled at the end of the season in October 2007, was performed as described by Cambardella and Elliott (1992). Dry soil samples of 30 g (<2 mm) were dispersed by shaking for 16 h on a reciprocal shaker in 100 mL of 5 g L^{-1} sodium hexametaphosphate [Na(PO$_3$)$_6$] solution. After dispersion, the soil was passed through a 53-μm sieve, rinsed several times with deionized water, and the slurry passing through the sieve was collected and dried in a forced-air oven at 50°C to constant weight. The dried samples were ground with a mortar and pestle and analyzed for total C by combustion on a LECO WR-12 C autoanalyzer (LECO Corp.). The difference between the C

content of the slurry and that of the duplicate undispersed soil was considered to be the C retained on the 53-μm sieve.

Soil inorganic P was extracted by a $NaHCO_3$ + NH_4F solution, buffered at pH 8.5 (Dabin, 1967). Soil for NH_4–N and NO_3–N determination was extracted with 1 mol L^{-1} KCl and analyzed by the salicylate–nitroprusside and the hydrazine–sulfanilamide methods, respectively (Mulvaney, 1996) after filtration through a glass fiber filter. For total N and total P, plant tissues and soil solution samples were digested using a modified Kjeldahl Li_2SO_4–H_2SO_4 procedure (Parkinson and Allen, 1975). Nitrogen in the digest was determined by the salicylate–nitroprusside procedure (Mulvaney, 1996). Extracts, soil solution samples, and digests were analyzed for orthophosphate by the molybdenum blue colorimetric method (Murphy and Riley, 1962) after pH adjustment using a 5 mol L^{-1} NaOH solution when necessary. In the ($NaHCO_3$ + NH_4F)-P determination (Dabin, 1967), interference of F^- with color formation was prevented using a 0.8 mol L^{-1} H_3BO_3 solution.

Statistical Analysis

The PROC MIXED (SAS Institute, 1999) procedure was used for the statistical analysis of the split-plot design data. Yield and biomass data for peanut in 2004 and 2006 or for millet in 2005 and 2007 were treated as repeated measures in time and analyzed as a split-split plot, with year as the whole-plot factor. The error term for the year effect was Block × Year. The error term for the shrub effect was Block × Year × Shrub. Contrasts ($P < 0.05$ unless otherwise noted) were used to assess the shrub vs. no shrub effect at different fertilizer levels. Additionally, fertilizer rate was treated as a quantitative factor and a direct regression approach (PROC MIXED) was used to examine a linear or quadratic fit of fertilizer rate on crop yield, crop biomass, or crop nutrient uptake. The fertilizer effect on *P. reticulatum* biomass and N and P in the biomass was restricted to the main plots with shrubs and analyzed as a randomized complete block design (PROC GLM).

Shrub biomass data were also normalized to a per-shrub basis (total biomass or biomass nutrient uptake as kilograms of nutrient per plot/number of shrubs per plot) and biomass and associated N and P were regressed on N and P rates using PROC REG (SAS Institute, 1999). For soil data, within each year, soil extractable N and P for the different sampling dates were analyzed as repeated measures in time (SAS Institute, 1999). Mean separation for significant effects was performed with Tukey's honest significant difference test ($P < 0.05$).

RESULTS AND DISCUSSION
Crop Yield

Peanut response to fertilizer in the presence or absence of shrubs varied with year ($P < 0.0001$), with a higher yield in 2006 than in 2004 (Table 1) (1304 and 601 kg ha^{-1}, respectively; values averaged across shrub–no shrub and fertilizer rates), which was probably due to differences in rainfall between the years. For millet, the year effect was not significant ($P > 0.20$), with mean grain yields of 1311 and 1182 kg ha^{-1} for 2005 and 2007, respectively. The ANOVA showed that there was a significant shrub effect on crop yield in 2004 and 2006 and a significant fertilizer effect in 2005, 2006, and 2007. In 2004, the peanut yield was significantly higher ($P < 0.05$) in the presence of shrubs

(660 kg ha^{-1}) than when there were no shrubs (553 kg ha^{-1}). This positive shrub effect was also observed in 2005 on millet except at the highest fertilizer rate. In 2006, the shrub effect was reversed, and plots with shrubs had lower yields than plots without shrubs (peanut grain yields of 1177 and 1430 kg ha^{-1}, respectively). In the 2007 season, plots with shrubs yielded slightly lower than plots without shrubs except at the 1.5× recommended fertilizer rate, but the differences were not significant.

The positive effect of shrubs on crop yield was only seen during the 2004 and 2006 seasons. For the subsequent 2 yr, the shrub effect was negative or nonsignificant. These crop productivity results for *P. reticulatum* stand in contrast to *G. senegalensis*, for which Dossa et al. (2012) showed a consistent increase in the yields of millet and peanut in the presence of *G. senegalensis* (similar shrub density) across most fertilizer rates ranging from zero to 1.5 times the recommended fertilizer rate. It is difficult to isolate the shrub species effect for comparison because the study by Dossa et al. (2012) was done at a site in northern Senegal where the soil has a much higher sand content and a drier environment (450 vs. 750 mm mean annual rainfall). Wezel et al. (2000) reported that the magnitude of the "fertile island" effect created by shrubs increased along a decreasing precipitation gradient.

The results of Dossa et al. (2010), however, do suggest that there could be a species effect based on their impacts on soils. They showed, at the same experimental site, that *G. senegalensis* induced greater C and N enrichment in its rhizosphere than did *P. reticulatum*, which may partly explain the contrast in shrub impact on crop productivity in our current study. Both of these shrub species have been shown to perform hydraulic lift, the movement of water from the wet subsoil to the dry surface soil (Kizito et al., 2012), and do not compete with millet for water (Kizito et al., 2007). Thus, *P. reticulatum* is not likely to negatively affect crops because of water relations. It may well be that the less water stressed environment and the naturally more fertile soils (higher clay and total C and N contents) at the *P. reticulatum* site reduced the potential for shrubs to improve crop productivity.

No fertilizer effect was observed with peanut in 2004 (Table 1), which can be attributed to reduced rainfall that year in the early growing season, which resulted in replanting the first seeding (total seasonal rainfall of 740 mm was just below the long-term average of 750 mm, but much of the rain came too late to offset the early-season deficit). Additionally, the disturbance of reseeding, which involved uprooting and replanting peanut, during the 2004 season might also have affected crop–fertilizer relations. Regression analysis showed that the fertilizer effect on millet yield was best fitted to a linear model ($P < 0.001$) in 2005 and 2007, with a significant shrub × fertilizer interaction in 2005 ($P < 0.05$). For peanut yield in 2006, a linear fit was significant ($P < 0.001$), and there was no shrub × fertilizer interaction ($P > 0.05$).

This linear response of millet grain yield to fertilizer was typical and expected for the Sahelian environment (Bationo et al., 1993; Dossa et al., 2012). The fertilizer effect on crop yield was more apparent in 2005 when water was not limiting crop growth (M. Sene, personal communication, 2011). The millet yield levels obtained in our study are within the yield ranges previously reported (Dancette, 1980; van Duivenbooden and Cissé, 1993;

Table 1. Crop yield of peanut or pearl millet as affected by the presence of shrubs (*Piliostigma reticulatum*) and fertilizer rate during four growing seasons at Nioro in Senegal.

	Crop yield											
	2004 (*Arachis hypogaea*)			2005 (*Pennisetum glaucum*)			2006 (*Arachis hypogaea*)			2007 (*Pennisetum glaucum*)		
Fertilizer rate	Shrub	No shrub	Mean	Shrub	No shrub	Mean	Shrub	No shrub	Mean	Shrub	No shrub	Mean
						—— kg ha^{-1} ——						
0	697 a†	637 a	667	854 a	652 b	753	1056 a	1139 a	1097	836 a	865 a	851
0.5×	639 a	551 b	595	1305 a	1072 b	1188	1174 a	1368 a	1271	1191 a	1285 a	1238
1×	699 a	461 b	580	1563 a	1492 a	1528	1160 b	1562 a	1361	1230 a	1297 a	1263
1.5×	606 a	522 b	564	1678 a	1869 a	1774	1319 b	1653 a	1486	1466 a	1288 a	1377
Mean	660 a	553 b		1350 a	1271 a		1177 b	1430 a		1180 a	1183 a	
Trend analysis across fertilizer rate	Shrub	No shrub	Combined	Shrub	No shrub	Combined	Shrub	No shrub	Combined	Shrub	No shrub	Combined
Linear	ns	ns	ns	***	***	***	*	**	***	***	*	***
Quadratic	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
Shrub × linear	–‡	–	–	–	–	**	–	–	ns	–	–	ns
Shrub × quadratic	–	–	–	–	–	ns	–	–	ns	–	–	ns

* Significant linear or quadratic effects of fertilizer at P < 0.05; ns, not significant.
** Significant linear or quadratic effects of fertilizer at P < 0.01.
*** Significant linear or quadratic effects of fertilizer at P < 0.001.
† Each pair of shrub and no-shrub means within a fertilizer rate (or averaged across fertilizer rates) and year followed by the same letter are not statistically different at P < 0.05.
‡ Not applicable.

Diangar et al., 2004) and were generally higher than a similar study in Senegal where millet and peanut were intercropped with *G. senegalensis* at a drier site (Dossa et al., 2012).

Crop Biomass and Nitrogen and Phosphorus Uptake

In cropping seasons 2004 and 2005, *P. reticulatum* had a significant effect on crop biomass production (P < 0.05). Peanut biomass was lowest for peanut-only plots receiving no fertilizer and highest in plots with shrubs receiving the highest fertilizer rate (Table 2). Nitrogen and P uptake during the 3 yr when data was collected generally was greater in the presence of the shrubs, except at the 1.5× fertilizer rate in 2007 and the 0.5× fertilizer rate for N in 2004 and 2005. In 2005, the millet crop had an overall significant difference between shrub and no-shrub plots for N and P uptake (Table 2). Total crop N uptake ranged from 20 to 30 kg N ha^{-1}, whereas P uptake varied from 1.5 to 3 kg P ha^{-1} (Table 2); however, these biomass and nutrient uptake values are presumably underestimated for 2004 because of plant residue losses due to defoliation by grasshoppers.

The effect of *P. reticulatum* on millet biomass and N and P uptake was not consistent during the 3 yr in which these properties were measured (Table 2). This stands in contrast to the results for *G. senegalensis*, where there was an overall significant and positive shrub effect on these properties for the same time period (except for N on millet in 2007) (Dossa et al., 2012). As mentioned above for crop yield, the site for *P. reticulatum* is under less water stress and has a more naturally fertile soil, suggesting that shrub response is greater in a stressed environment.

Shrub biomass and N uptake in the biomass during all three growing seasons were comparatively higher in our study (Table 2) than those at the northern Senegal site for the *G. senegalensis* study (Dossa et al., 2012) at all fertilizer rates. Conversely, P uptake in the biomass was generally lower in the current study than that reported by Dossa et al. (2012). In cropping seasons 2006 and 2007, crop biomass yields were quite stable—millet biomass varied only from 1419 to 1466 kg ha^{-1} in the absence of shrubs and from 1625 to1897 kg ha^{-1} in the presence of shrubs.

Piliostigma reticulatum Biomass and Nitrogen and Phosphorus Uptake

Piliostigma reticulatum biomass N uptake was typically the highest for the zero fertilizer treatment, and to some extent tended to decrease or stay the same with increasing fertilizer between 0.5 and 1.5 times the recommended rate (Fig. 2). The initial shrub biomass differences among plots probably contributed to this. There was no effect of fertilizer application rates on shrub biomass and N and P uptake by *P. reticulatum* when the shrub biomass and the nutrients in the biomass were normalized on a single-shrub basis (total biomass or biomass nutrient uptake/number of shrubs per plot) (data not shown).

Our results showed a poor relationship between shrub biomass or N and P uptake with increasing fertilizer rates. This stands in contrast to *G. senegalensis* in drier northern

Table 2. Aboveground crop biomass and nutrient uptake in the presence or absence of *Piliostigma reticulatum* under various rates of fertilizer during three growing seasons at Nioro in Senegal.

Fertilizer rate	2004 (*Arachis hypogaea*) Biomass Shrub	Biomass No shrub	N Shrub	N No Shrub	P Shrub	P No Shrub	2005 (*Pennisetum glaucum*) Biomass Shrub	Biomass No shrub	N Shrub	N No shrub	P Shrub	P No shrub	2007 (*Pennisetum glaucum*) Biomass Shrub	Biomass No shrub	N Shrub	N No shrub	P Shrub	P No shrub
									— kg ha^{-1} —									
0	1235 a†	1126 a	21.4 a	20.2 a	1.8 a	1.6 a	1897 a	1419 a	22.0 a	14.4 a	1.7 a	1.5 a	1625 a	1466 a	20.3 a	18.9 a	1.6 a	1.1 a
0.5×	1241 a	1231 a	21.9 a	22.6 a	1.8 a	1.7 a	2761 a	2179 b	27.6 a	29.9 a	2.3 a	2.3 a	2609 a	2836 a	31.9 a	27.5 a	3.5 a	2.2 a
1×	1552 a	1259 b	30.2 a	25.2 a	2.5 a	2.2 a	3930 a	2622 b	45.6 a	40.2 a	3.6 a	3.7 a	4210 a	4099 a	52.8 a	43.3 a	5.7 a	4.9 a
1.5×	1574 a	1313 b	31.1 a	22.0 a	2.8 a	2.1 a	4806 a	3684 b	57.2 a	38.3 b	5.9 a	3.7 b	5199 a	5276 a	67.1 a	73.4 a	9.6 a	12.1 a
Mean	1400 a	1232 b	26.2 a	22.5 a	2.2 a	1.9 a	3349 a	2475 b	38.2 a	30.7 b	3.3 a	2.8 b	3410 a	3419 a	43.0 a	40.1 a	5.1 a	5.0 a
Trend analysis across fertilizer rates																		
Linear	*		ns		**		***		***		***		***		***		***	
Quadratic	ns		ns		ns		ns		ns		ns		ns		*		*	
Shrub × linear	ns		ns		ns		ns		*		*		ns		ns		*	
Shrub × quadratic	ns		ns		ns		ns		*		*		ns		ns		*	

* Significant linear or quadratic effects of fertilizer at $P < 0.05$; ns, not significant.

** Significant linear or quadratic effects of fertilizer at $P < 0.01$.

*** Significant linear or quadratic effects of fertilizer at $P < 0.001$.

† Each pair of means between shrub and no-shrub treatments for biomass, N uptake, or P uptake within a year and fertilizer rate (or averaged across fertilizer rates) followed by the same letter are not significantly different at $P < 0.05$.

Senegal, where a quasi-linear and positive relationship was found for these parameters with fertilizer rate (Dossa et al., 2012). This indicates that *G. senegalensis* might be scavenging residual fertilizer nutrients, which results in improvement of nutrient use efficiency by recycling nutrients in the biomass. This did not seem to be the case for *P. reticulatum* relative to nutrient uptake or shrub aboveground biomass production.

Particulate Organic Matter

Particulate organic C analysis showed that plots with shrubs had significantly higher ($P < 0.05$) POM content (1432 mg C kg^{-1}) than plots without shrubs (932 mg C kg^{-1}). This is undoubtedly due to the litter input and root turnover from the shrubs. This is a significant benefit of *P. reticulatum* because POM is important in increasing the soil quality. Particulate organic matter can improve the soil structure directly by acting as an aggregate (Jastrow, 1996; Bayer et al., 2002; Diekow et al., 2005) and by providing substrate for microbial activity, which can also promote the formation of aggregates during decomposition. Thus, a better structured soil with greater porosity can improve water use efficiency by increasing the water holding capacity.

There was a positive trend for a relationship between POM content and millet yield, but regression analysis resulted in a low R^2 value of 0.30 (Fig. 3). This stands in contrast to the strong and positive relationship of millet yield with soil POM reported by Dossa et al. (2012) in soils with or without the presence of *G. senegalensis* at the drier site in the Peanut Basin in northern Senegal. This weak relationship could be due to a relatively higher inherent soil fertility index at the Nioro site compared with the drier *G. senegalensis* study site (Dossa et al., 2012). Wezel et al. (2000) reported that the "fertile islands" effect of shrubs in the semiarid environment of Niger increased along a decreasing precipitation gradient.

Extractable Soil Nitrogen and Phosphorus Dynamics

Extractable soil NO_3 and NH_4 values were summed because the levels of these ions in the soil solution were low. In 2004, the extractable inorganic N content of the soil decreased through the growing season but then increased at the end of the season (Fig. 4). The fertilization rate had no significant effect ($P > 0.05$) on the soil inorganic N content. The presence of the shrubs, however, significantly improved ($P < 0.05$) the soil inorganic N content over that of the millet-only plots, supporting the concept that *P. reticulatum* creates islands of fertility.

The soil inorganic N content in 2005 dropped rapidly to lower levels than in 2004 and demonstrated the very rapid temporal dynamics in sandy soils. The differences in N content in 2004 and 2005 could be due to differences in soil biology, seasonal climatic differences (rainfall and temperature), and leaching of NO_3 (which increases with greater rainfall). Dossa et al. (2012) also observed a similar drop in inorganic N content at the drier site in northern Senegal in the *G. senegalensis* intercropping system in 2005. The soil types at the *G. senegalensis* and *P. reticulatum* sites are different. The soils at the *G. senegalensis* site
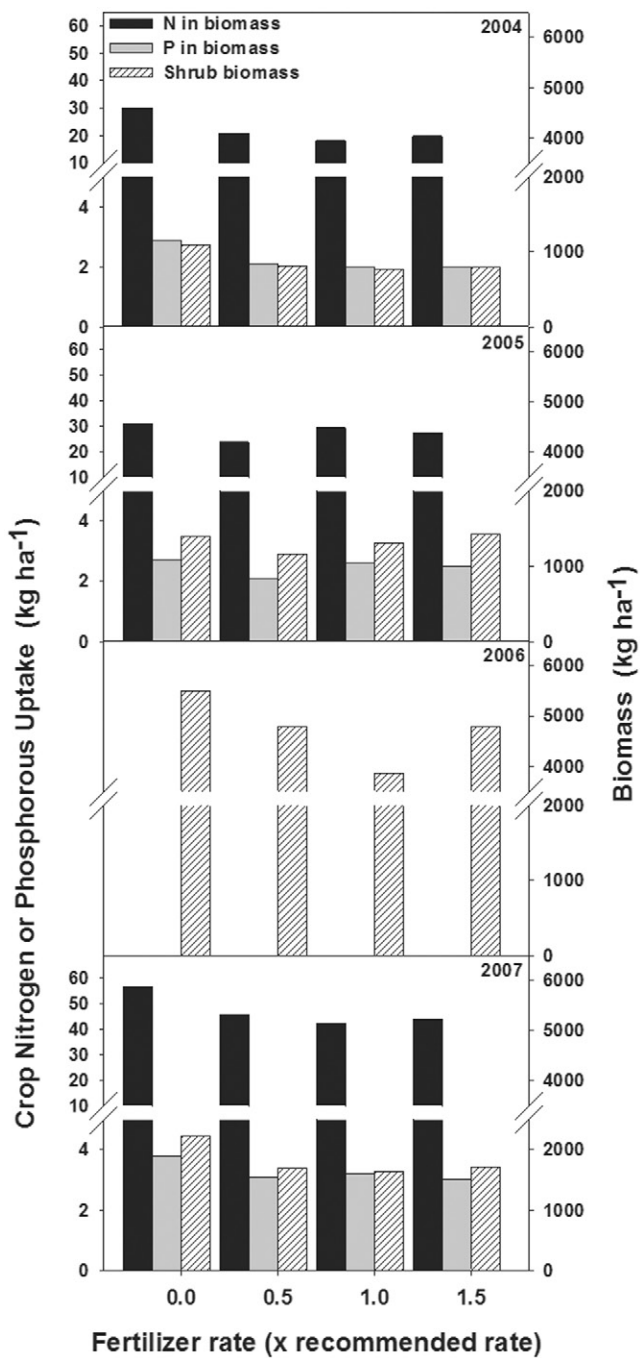
Fig. 2. Biomass and nutrient uptake of *Piliostigma reticulatum* under varying rates of fertilizer applied to crops at Nioro, Senegal.
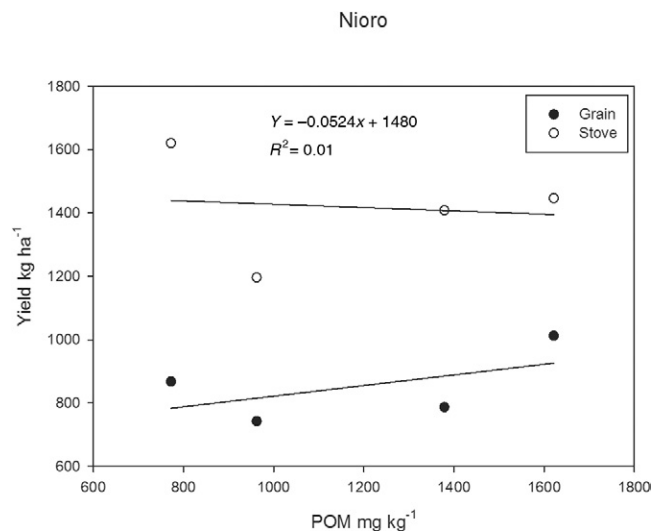

Fig. 3. Relationship between particulate organic matter (POM) content of soil (0–10-cm depth) and millet grain yield or biomass in the presence or absence of *Piliostigma reticulatum* at Nioro, Senegal. Data are from the 2007 season.

not shown) that soil conditions at the Nioro site were quite moist at the end of the 2005 season, whereas those at the northern site were dry (Dossa et al., 2012). In the absence of shrubs, the soil had roughly the same rapid decrease in soil N content throughout the growing season in 2005 (Fig. 4).

The trend of soil inorganic N in the 2007 season showed roughly the same rapid decrease in soil N content throughout the growing season followed by a rise in N concentrations at the end of the season in the absence of shrubs. The decrease in soil N content early in the growing season might be due to microbial and crop uptake of N and leaching or runoff losses. The low levels of N in 2005 when rainfall was above average compared with the dry year of 2004, which had higher N levels, supports the idea that leaching of N is occurring in these soils. These results support a recommendation to split the application of N to the soil, instead of applying all of it at planting, to reduce potential losses from N leaching and to improve N use efficiency.

In 2004, extractable soil P initially showed a decrease and then a rise in concentration at the end of the season (Fig. 5). The extractable P content of the soils was not affected by the presence of shrubs but was significantly affected by the fertilizer rate ($P < 0.01$), with extractable P generally increasing with increasing P fertilizer rates. In 2005, soil P initially increased until August and thereafter decreased until the end of the season (Fig. 5). In 2007, soil extractable P increased significantly ($P < 0.001$) with increasing fertilizer rate, with the highest levels observed with the highest rate of applied fertilizer.

Extractable P was not affected by the presence of shrubs, which is probably a reflection of both soil type and the root architecture of *P. reticulatum*. This stands in contrast to the study of *G. senegalensis* in the drier northern site of Senegal, where soil extractable P was higher with shrubs than without shrubs (Dossa et al., 2012). The soil at the *P. reticulatum* site has a greater amount of weathered clay and Fe precipitates on soil mineral surfaces, which buffers the soil to hold P. Additionally, *P. reticulatum* has a single tap root and limited root branching and may therefore have less potential to take up P,

exhibited a rise in N content at the end of the season, whereas in the present study there was a steady decrease in N concentrations during the season except for 2007 in the absence of shrubs, when all N fertilizer rates increased inorganic N levels (Fig. 4). This was probably because the current northern site has greater rainfall and a more extended rainy period that promotes the leaching of NO_3.

When end-of-season soil samples coincided with a dry spell, as in 2004 and 2007 in the absence of shrubs (the soil is wetter in the shrub vicinity than outside the shrub influence, see Kizito et al., 2007), the same soil N content was observed, which is attributed to the release of nutrients on microbial death (Brookes et al., 1982). This is supported by our observation (data
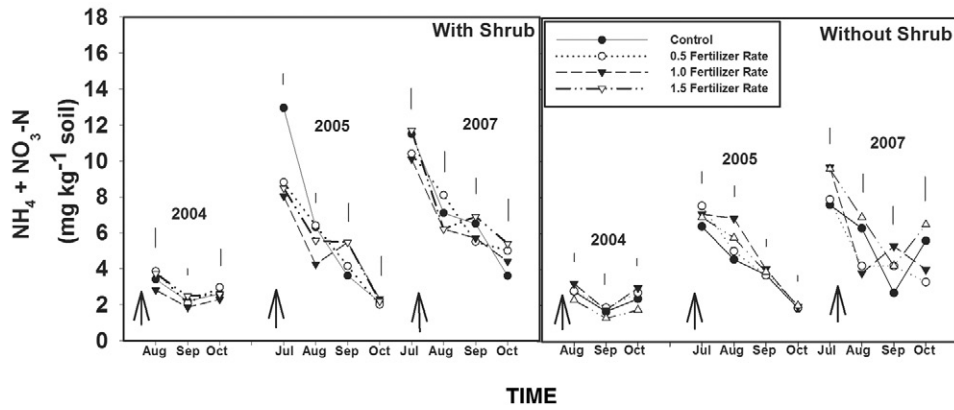
Fig. 4. Inorganic N dynamics in soils as affected by the presence of *Piliostigma reticulatum* and fertilizer rate at Nioro, Senegal, in 2004, 2005, and 2007 seasons. Arrows represent fertilization events. Vertical bars are means separation using Tukey's honest significant difference at *P* < 0.05.
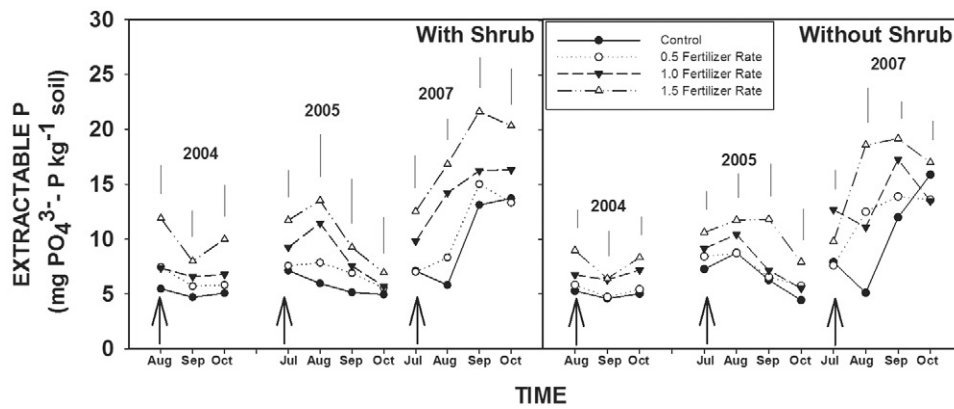

Fig. 5. Extractable P dynamics in soils as affected by the presence of *Piliostigma reticulatum* and fertilizer rate at Nioro, Senegal, in 2004, 2005, and 2007 seasons. Arrows represent fertilization events. Vertical bars are means separation using Tukey's honest significant difference at *P* < 0.05.
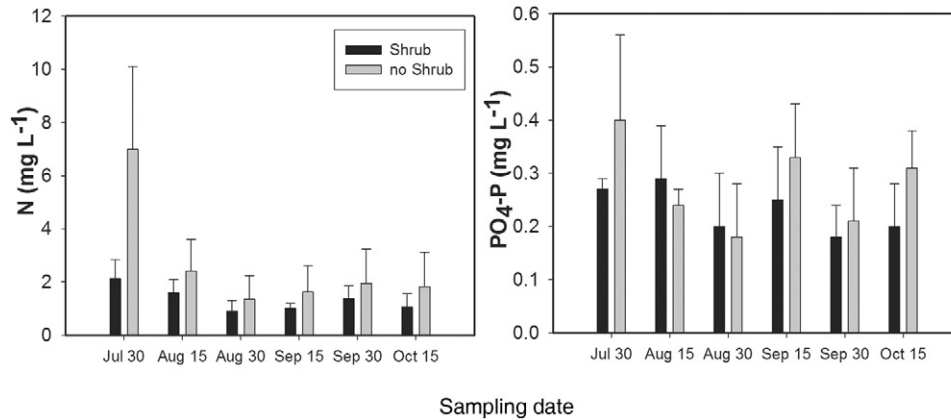

Fig. 6. Temporal variation of N (left) and P (right) concentrations of soil leachates beneath millet in the presence or absence of shrubs at Nioro, Senegal. Data are from the 2005 growing season. Bars represent standard errors of the mean.

whereas *G. senegalensis* has a diffuse, fibrous, and spreading root system (Kizito et al., 2006).

A typical example of the N and P leachate data for all years is shown in Fig. 6 for the 2005 cropping season at the 1.5× fertilizer rate treatment. The N concentration in soil leachates showed higher variability and typically the highest values in early samplings. The N concentration of leachates was consistently lower under shrub plots than in millet-only plots, indicating that shrubs are recovering N and less is being lost by leaching at the 1.5× fertilizer rate (Fig. 6), but this effect became less evident at the 0.5× fertilizer rate and showed no shrub effect at the zero fertilizer rate (data not shown). Thus, shrubs might be conserving mobile nutrients such as N under the sandy soil conditions of the Sahel. Contrary to N, the P

concentration in soil leachates had wide variability and did not show any significant shrub system effect. This may be because phosphate is strongly controlled by sorption reactions (Dossa et al., 2008) and is relatively immobile in soil profiles.

CONCLUSIONS AND PERSPECTIVES

From an ecological and soil quality perspective, the results of this study indicate that *P. reticulatum* is delivering agroecosystem services. The most obvious response for improving soils was an increase in POM in the presence of the shrubs because POM promotes aggregation for improved root growth and water relations for adjacent crops. *Pilisotigma. reticulatum* is recovering N and reducing leaching of that element, thus enabling the conservation and recycling of N through subsequent litter inputs and root turnover.

In 3 of the 4 yr, crop yields were either unaffected or increased in the presence of *P. reticulatum*. Millet yield was positively or not affected by *P. reticulatum*. This would suggest there is little or no competition of the shrub with millet based on crop yields, which is consistent with Kizito et al. (2007), who showed that there was no competition for water between these two plant species. Peanut, however, increased or decreased in yield in the presence of *P. reticulatum*. These results are in contrast to the study of Dossa et al. (2012), where the presence of *G. senegalensis* had highly significant yield increases for both peanut and millet crops during a 4-yr period at a drier site with a sandier soil in northern Senegal. Comparison of these two studies suggests that shrubs could have a more direct positive impact on crop productivity in water-stressed environments. Although it appears that *P. reticulatum* in cropped fields provides some ecological benefits, more research is needed for longer periods than the current study, along with direct comparisons of *P. reticulatum* and *G. senegalensis* on the same site to determine the relative benefits of these two species in promoting crop productivity.

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